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Research paper

The use of natural fibers in stone mastic asphalt mixtures: a review of the literature

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Abstract: All over the world, highway traffic is increasing rapidly, as is the population and the road network. The country's maximum and minimum temperatures also vary greatly. Moreover, the pavements are subjected to various types of damage. Pavement binders and mixtures are a constant area of research and development for scientists and engineers. Adding fibers to bituminous mixes may improve the properties of fatigue and strength of the material. Natural fibers may be used to improve asphalt mixtures performance due to their inherent compatibility with asphalt cement and excellent mechanical properties. Also, the high stone content and relatively high asphalt content in SMA mixture led to the occurrence of drain-down of the asphalt mastic from the mixture, and this problem requires the use of stabilizing additives such as cellulose fibers, mineral fibers, or polymers to mitigate this problem and ensure long-term performance. The most public sort of stabilizing additives is cellulose fiber. Overall, natural fibers in stone mastic asphalt mixes are discussed in this paper. An additional focus is on how asphalt concrete will be affected by natural fibers, mixing techniques, and managerial decisions. According to the review, the stabilizing and strengthening impact of natural fibers on the performance of asphalt mixes have been extensively researched. Natural fibers can significantly increase the rut and flow resistance of asphalt mixtures. Adding natural fibers to pavement can increase structural resistance to pavement distress.

Keywords: cellulose fibers, mechanical properties, natural fibers, optimum fiber content, Stone Mastic Asphalt, waste fibers

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1. Introduction

Gap-graded asphalt mixture (Stone Mastic Asphalt) has a high proportion of coarse aggregate, asphalt, and polymer or fiber stabilizers [1]. A high concentration of coarse aggregate is necessary to provide the desired strength and durability, while an abundance of mortar binder is required. This is due to the omitting of some fine aggregate in the aggregate gradation of SMA mix, which requires compensation by adding more asphalt binder [2, 3]. Stabilizing additives may be added to SMA mixtures to keep the asphalt in the mix at elevated temperatures, reduce drain-down amid production, transport, and laying, and improve overall performance [2, 4–12]. Mineral and jute fibers are naturally occurring fibers found in SMA blends. Synthetic fibers such as cellulose, polyester, and polypropylene are examples of manmade fibers [13–15].

There are many primary functions of fiber reinforcement in asphalt mixes, including increasing the tensile strength of the resulting asphalt concrete, and reducing the development and spread of cracking that could weaken integrity of road pavement structure [14, 16]. Papers [17] and [18] found that fibers improve the service properties of the asphalt mixture by forming micromesh in the asphalt mixture to prevent the asphalt from draining down and thus increasing the mix durability AND stability [8, 19]. Asphalt mixtures with fibers can withstand permanent deformation and fatigue cracking [7, 14, 16, 20]. However, it was discovered that natural fibers have high hygroscopicity issues, impeded free fibers distribution in the mixer, clumping tendency, and a high probability of scorching when free fibers fall onto superheated inert material in the mixer [3].

In the case of mixtures with discontinuous grading, gap graded mixtures, the resulting mixture tends to be more stable and possibly more resistant to rutting and fatigue cracking due to stone-on-stone contact that could be provided by the coarse aggregate skeleton, while the high binder content mortar provides durability [21–26]. In addition, the mineral filler is more abundant in SMA than dense-graded mixtures, which have a higher percentage of coarse aggregate. SMA is resistant to permanent deformation and is capable of providing long-term behavior and strength [6, 27, 28], high resistance to reflective cracking and low noise pollution [24]. Asphalt binder, mineral filler, fine aggregate, and stabilizing additive typically make up the mortar. SMA mixtures' tensile strength and cohesion can be strengthened and improved with this stabilizing additive [23]. Nevertheless, drain-down of asphalt binder and the relatively high initial costs could be mentioned as its disadvantages [5, 29].

Stabilizers and modified binders have been tested in SMA by researchers around the world to reduce binder drain-down and improve performance characteristics. In SMA, [21] used stabilizers such as styrene-butadiene-styrene (SBS), polyolefin, cellulose fiber and rock wool fiber. Fiber stabilizers are more effective than polymer stabilizers in reducing drain-down. Polymer-modified mixtures, on the other hand, performed better in rutting resistance.

In 2006, Muniandy and Huat utilized natural cellulose fiber from oil palm to improve the fatigue behavior characteristics of SMAs. It was seen that the utilization of cellulose oil palm fiber (COPF) enhances SMA's fatigue performance, tensile stress and stiffness, especially at a fiber content of about 0.6%. Research by [30] investigated the drain-down values of SMA mixtures using three different sorts of cellulose-based modifiers. They found all three cellulose-based additive SMA mixtures performed better than those without. A study by [6] found no drain-down when using coir fiber in SMA and concluded that adding fiber (coir) effectively controls the drain-down of SMA mixtures.

Natural fibers like hemp, sisal, coir, banana, and other types are used in the highway industry today. The stability could be increased by increasing fibers in SMA and open-graded-friction (OGF) mixtures. In addition, the use of natural fibers gives better strength, and durability and prevents the drain-down of bitumen from the mix [5, 8, 19, 31–33]. Natural fibers have also been shown to be preferred over other additives in trials and practical experience because they are easy to handle, temperature inert, and have the optimal effect on reducing asphalt binder drain-down. Adding fiber to an asphalt mix alters its viscoelastic properties [34]; improves the dynamic modulus [35], decreases the mixture's susceptibility to moisture [29], improves creep compliance and the resistance to rutting [16]; and decreases the mixture's reflective cracking [16, 36, 37].

The fiber content and length are critical issues affecting stability, flow, and volumetric attributes of HMA mixes. Stability could be enhanced because of the fibers' additional resistance, while flow is reduced because of the fibers' resistance to deformation. Because of the fibers ability to absorb the asphalt binder needed to coat the aggregate, the air voids will be increased [16, 38]. Large fibers can reduce the aggregates' contact points, resulting in a decrease in stability and an increase in flow [39].

Many researchers have recently been interested in the use of fibers in asphalt modification. Recent studies have shown that fibers are more effective than polymer materials at reducing drain-down of AC mixes in stone mastic asphalt and open-graded friction courses [32]. Fiber–asphalt mixture has a slightly higher optimum asphalt binder content than the pure asphalt mixture in terms of efficiency. When fibers are added, a similar analogy can be drawn between asphalt and fine aggregates. Fibers, on the other hand, can be used to keep asphalt from leaking due to the cling of asphalt to fibers [40]. This research shows good moisture resistance, creep compliance, and rutting resistance for fiber–asphalt mixtures, in addition to low-temperature anti-cracking properties and longevity [40]. Asphalt fiber modification is a complex process, however, the impact on pavement performance is significant.

From the above, it is clear that the use of natural fibers in the industry is not new in the field of improving the engineering properties of building materials to form a composite structure with greater strength and less weight than traditional parts and also in reinforced concrete, as well as insulators in buildings. However, the utilization of natural fibers in bituminous mixes differs, as their main function is not to strengthen the asphalt mixture, but as a thickener to bind asphalt to prevent unwanted drainage, especially in open-graded mixtures such as stone mastic asphalt mastic.

Many Iraqi roads have been damaged due to harsh weather conditions, especially high temperatures during the summer, which causes damage to the paving such as rutting and fatigue. By reviewing previous recent studies, it has been shown that damage caused in pavement can be reduced by gap graded mixtures such as SMA instead of conventional mixtures. In Iraq, SMA utilization is very limited due to a lack of specification. This acquires appropriate investigations in the use of SMA and the proper additives and modifiers to enhance the performance of the asphalt mixes. Usually, expensive synthetic fibers are used to limit the drain down problem of SMA mixes. Replacing these expensive synthetic fibers with renewable materials such as natural fibers is economically important. The current research work reviews the effect of natural fibers as stabilizing agents in Stone Mastic asphalt mixtures and their role in the engineering properties of the mixture.

2. Stone mastic asphalt

Stone Mastic Asphalt (SMA) was first introduced in Europe for its ability to withstand damage from studded tires. A national standard was established in Germany in 1984 in recognition of its outstanding performance. SMA is a good option for long-lasting pavements because of its well-enhanced field performance on test tracks and in other parts of developed countries with a variety of climates [21, 41, 42].

Bituminous material with a high percentage of filler and coarse aggregate is known as Stone Mastic Asphalt. A waterproof layer with good surface drainage is formed with only 4% air voids and a high level of macro texture when the material is laid down. Due to their flexibility, asphalt mixtures can resist permanent deformation caused by heavy vehicle traffic without compromising pavement performance [11, 27, 29, 33, 43, 44]. Fatigue cracking and rutting along the wheel tracks of pavements are caused by traffic loads that are repeatedly applied. Stone Mastic Asphalt (SMA) was developed in Germany in the mid-1960s to address these issues. Gap-graded SMA is composed of a coarse aggregate skeleton and a mortar with a high binder content, about 6–7% [27, 29]. Stone-to-stone contact with good interlocking and a high binder content mortar gives SMA its high concentration of stability skeleton. Mortar typically includes asphalt binder, mineral filler, fine aggregate, and stabilizing additive [17, 45, 46]. Mastic has a high concentration of binder, so it requires stabilizing additives to keep the binder from separating out. Stabilizing additives in SMA typically consist of polymers and fibers [2, 47].

Intersections and other areas with heavy traffic have successfully benefited from the use of Stone Mastic Asphalt. Stone Mastic asphalt is costly and this cost is related to the addition of mineral fillers such as hydrated lime, stone dust and fly ash, fibers like natural fibers and synthetic fibers, modified binder, and higher asphalt contents may be possible [11, 33].

3. Natural fibers

Growing awareness of the environmental impact of synthetic materials has led to develop materials with eco-friendly properties. The academics are keen on developing materials that can replace synthetics. As a result, natural fiber-based composites have become increasingly popular in various industrial sectors. Natural fibers are lightweight, low-cost, renewable, biodegradable, and have high specific properties. The durability of natural fiber-based composite materials has increased their use in various industries. It is well documented that natural fibers' major uses and their effectiveness are as polymer composite reinforcement. However, the main disadvantage is the incompatibility and high moisture absorption of natural fibers from plants and animals. Thus, chemical treatments of natural fibers have improved the adhesion of fibers to the mastic and improved the mechanical properties of composites. Shortly, natural fiber will become a renewable resource that could substitute synthetic fibers in many usages [48].

Depending on where they come from, natural fibers can be divided into bast (like jute and banana) and leaf (like pineapple, screw pine, and henequen), or fruit or seed fibers (coir, palm, and cotton). Natural fiber composites have been made using a variety of fiber arrangements, including short-randomly oriented, long-unidirectional, and woven fabrics. The best material for reinforcing bituminous mixes is fiber, the most common reinforcing material [14].

Plant fibers include waxes, cellulose, lignin, hemicellulose, pectin, and other water-soluble materials, as shown in Fig. 1. The presence of hydrophilic cellulose changes the interfacial binding between the fibers and the polymer matrix. One method of optimizing fiber-polymer interaction is to chemically treat natural fibers. Thus, it increases interfacial interaction between OH functional groups on fiber surfaces and increases the roughness of surface on fiber surfaces [48–52]. Table 1 presents the main components of some types of natural fibers. Cellulose is the major structural component of natural fibers followed by hemicellulose and lignin [14].

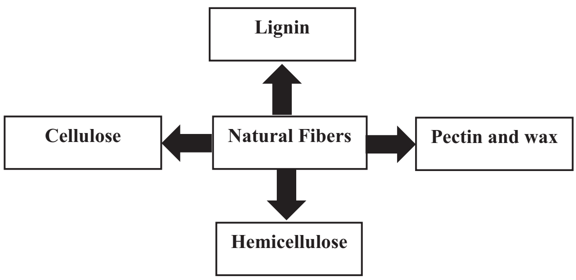

Fig. 1. Characteristics of the natural fibers [53]

Studies have proven that adding natural fibers could improve the fatigue resistance of SMA mixes by increasing the tensile strength [7, 20, 54, 55]. SMA mixtures are also superior at reducing drain-down and boosting resistance to long-term deformation [8, 19]. Additionally, they improve aggregate stone-to-stone contact and binder-aggregate adhesion, which reduces SMA mixture stripping. Also, it was proven that SMA blends containing natural fibers like sisal, coir, and banana fiber. Additionally, it was discovered that the addition of natural fibers to asphalt mixes with higher crushing resistance helps to increase their compressive strength [47].

Research by [9] investigated the use of various natural stabilizers such as coir fibers, oil palm fibers, and Jute fibers and compared them with some artificial stabilizers like fibers

Table 1. Structural composition of some natural fiber types [14]

Name of the fiber	Cellulose (wt.%)	Lignin (wt.%)	Hemicellulose (wt.%)	Pectin (wt.%)	Wax (wt.%)	Moisture content (wt.%)
Bast fiber						
Jute	61–71.5	12–13	13.6–20.4	0.2	0.5	12.6
Flax	71	2.2	18.6–20.6	2.3	1.7	10.0
Hemp	70.2–74.4	3.7–5.7	17.9–22.4	0.9	0.8	10.8
Ramie	68.6–76.2	0.6–0.7	13.1–16.7	1.9	0.3	8.0
Leaf fiber						
Sisal	67–78	8.0–11.0	10.0–14.2	10.0	2.0	11.0
Pineapple leaf	70–82	5–12	–	–	–	11.8
Seed fiber						
Cotton	82.7	0.7–1.6	5.7	0.6	0.6	33–34

extracted from refrigerator door panels, fibers extracted from old machinery belts, and glass fibers as drain-down retarders. The gradation of aggregate used in this study follows the IRC specifications for nominal maximum aggregate size of 13 mm. It is specified that the addition rate of cellulose fibers at a minimum of 0.3% with fiber length of 10 mm is optimum. When contrasted with the control mix, the performance of SMA mixes was found to be improved by the addition of inexpensive fibers as stabilizer additives. The stabilizers were more effective at delaying the asphalt drain-down from the SMA mixes.

4. Utilization of natural fibers in bituminous mixes

The binder matrix may drain down in SMA mixes because of the gap-graded structure. So fibers are used as stabilizers, preventing drain-down and increasing rut resistance. Fibers like cellulose, mineral, polymers, and plastics are commonly used. However, various studies are carried out using natural fibers like coir, sisal, banana, and jute fibers.

4.1. Bamboo fiber

Because of how the longitudinal fibers are aligned, bamboo fibers are also known as natural glass fibers [56, 57]. With 40 families and 400 species. This type of fibers is one of the most prevalent trees in dense forests, especially in East Asia [58, 59]. Bamboo fiber is utilized as a polymeric reinforcement because it is light, cheap, strong, and stiff [48, 56]. Bamboo fibers have a high tensile strength in the fiber direction and a rough surface texture similar to lignin fiber. Also, bamboo fiber is thermally stable, which is a concern for plant-based materials [55].

The literature review found few researches on utilizing bamboo fiber as road construction material. Bamboo fibers reportedly increase concrete beam flexural strength and elasticity modulus [61]. Using bamboo fiber increased the stability of SMA mixtures compared to cellulose fiber or no fiber [62]. However, natural fibers may have properties (e.g., hydrophilicity, high moisture absorption, and low degradation temperature) that limit their use in asphalt mixtures [55].

Paper [56] evaluated the use of bamboo fiber as a natural fiber in SMA and dense-graded asphalt mixtures for improved performance. It is found that bamboo fibers reportedly increase concrete beam flexural strength and modulus of elasticity, as well as increase the stability of SMA mixtures. The optimal bamboo fiber contents for DG and SMA mixtures were 0.2–0.3% and 0.4%, respectively (by weight of mixture).

Research by [62] investigate the mechanical properties of asphalt binders and mixtures under a range of loading and temperature conditions. Performance tests showed that adding bamboo fiber to asphalt mixtures enhanced their stiffness and cracking performance at an intermediate temperature, but these benefits diminished at higher temperatures. The photo of the bamboo fiber is shown in Fig. 2.

Fig. 2. Microscopic bamboo fiber [62]

4.2. Date palm fiber

Date palm is a fruit palm widely grown for its fruit. The date palm has around 19 species and over 5,000 cultivators worldwide [63, 64]. Date palms (Phoenix dactylifera L.) are the tallest Phoenix species, reaching up to 23 m as shown in Fig. 3 [65, 66]. After harvesting date farm fruits, date palm rachis and leaves accumulate in large quantities in various countries' farming lands. These fiber types could be utilized as cellulosic fibers. Leaves and rachis fibers could be utilized to reinforce thermoplastic and thermosetting polymers.

The fatigue performance of stone mastic asphalt reinforced with oil palm cellulose fiber was investigated by [22]. The common belief is that gap-graded mixes are more likely to fatigue over time. Researchers used 0.2, 0.4, 0.6, 0.8, and 1.0% fiber by weight of pre-blended cellulose fibers in PG64-22 binder. Properties such as fatigue life, tensile stress, and stiffness were all improved in the modified binders. Fatigue resistance was greatest at a fiber content of 0.6%.

(a) (b)

Fig. 3. Date Palm Fiber [69, 70]

4.3. Sisal fiber

Sisal is a widely used natural fiber. The rosette of leaves grows up to 1.5–2 m tall and is native to southern Mexico [67,68]. However, the main producers of sisal fibers are Tanzania and Brazil [69, 70]. Sisal fibers are utilized in the automotive, shipping (for mooring small craft and cargo handling), civil construction, elevator fiber cores, and agricultural twine or baler twine industries, among others [70, 71]. Sisal is traditionally the most selected agricultural material for twine binders due to long-term strength, ability to stretch, some dyestuffs affinity, and resistance to saltwater deterioration, see Fig. 4 [33]. Short sisal fibers delay restrained plastic shrinkage, which helps prevent early crack development, and the material is resistant to moisture and heat. Sisal fibers are used to reinforce houses in developing nations [14].

Research by [72] evaluated the use of natural fibers (sisal and coconut) in a SMA mixture in the field of hot mix asphalt. Performances were compared with (i) no fiber mixture, (ii) polyester fibers, and (iii) cellulose. Tensile strength and resilience modulus of natural fiber blends showed high resistance to mechanical tests (Table 2). The mixture with rubber-modified asphalt displayed the best fatigue behavior, while sisal, coconut shells, and cellulose fibers produced barely different results.

Fig. 4. Sisal fiber [33]

Table 2. Mechanical analysis of mixtures evaluated [72]

Mixture type	Modulus resistant (MPa)	Tensile strength (MPa)
CAPFLEX B without fiber	3.077	1.1
AC 50-70 without fiber	7.306	0.9
AC 50-70 with cellulose fiber	6.417	1.1
AC 50-70 with coconut fiber	7.948	1.1
AC 50-70 with sisal fiber	7.193	1.0
AC 50-70 with polyester	5.629	0.8

SMA and DGA formulations that included sisal fiber as a stabilizer or additive were the subject of research by [12] and [73] respectively. In both DGA and SMA blends, 0.3% was identified as the Optimal Fiber Content (OFC). Similar results were observed when determining the optimal binder content (OBC) for DGA and SMA; 5% and 5.2%, respectively. It is concluded that the addition of sisal fiber has enhanced the mix properties, such as Marshall Stability, drain down, and indirect tensile strength.

4.4. Jute fiber

The countries of India, Bangladesh, China, and Myanmar are the primary producers of jute [74,75]. After 4 months of cultivation, the jute plant will have grown 15–20 cm and the fibers can be harvested. The retting process can be carried out chemically (using $N_2H_8C_2O_4$, Na_2SO_3, etc.) or biologically [77,78]. Wetting harvested stalks for around 20 days is a key step in the biological retting process. In order to facilitate fiber separation, pectin is removed from the space between the bast and the wood core before the materials are dried (see Fig. 5) [48]. Fiber contains lignin in addition to waxes, sugars, minerals, and cellulose (including hemicellulose). The yearly renewability of jute material is a plus, and it also has the benefits of being strong, highly absorbent, environmentally friendly, biodegradable, and compostable. Table 3 displays the jute fiber's physical characteristics [13,14].

Fig. 5. Jute fiber

Table 3. Physical properties of Jute fibers

Property	Result
Average fiber length	5 mm maximum
Moisture content	$<$ 10% by weight
Ash content (non-volatile) (%)	20

Research by [18] investigated coated jute fiber as a substitute to synthetic fiber in bituminous pavement construction. According to the results, jute could substitute the synthetic fibers in the SMA mixes. The permanent deformation of the fiber-modified mixtures was identical, and the tensile strength ratio (97%) exceeds the limits of (70%). The construction cost per metric ton of SMA blends prepared with natural fibers was 18% lower than that of blends made with synthetic fiber. Jute has a good adhesion to asphalt, as evidenced by the widespread use of asphalt-impregnated jute fibers. Therefore, it seems logical to suggest jute as an asphalt overlay fabric. Paper [44] investigated the use of low viscosity binder-coated jute fiber as a substitute to traditional SMA Mix fibers. Comparing the results, 0.3% of the fiber was found to be optimal.

Research by [20] compared the behavior of stone mastic asphalt (SMA) mixes with and without jute fiber. Two synthetic fibers (acrylic and polyester) and one cellulose fiber (viscose) were considered waste fibers from automotive carpet manufacturing. Tests on the SMA mixes included drain-down, Marshall Stability, Marshall Stability Ratio, tensile strength, and compression strength loss. In addition, cohesion and internal friction angle were calculated. The cellulose fibers outperform synthetic fibers in stabilizing the binder content of SMA mixtures.

4.5. Cellulose fiber

Cellulose fibers are the most widely used in SMA mixtures. This fiber's main component is cellulose $(C_6H_{10}O_5)_n$, where $n = 1000$. This safe organic fiber is abundant in nature.

According to [79], it transports the bitumen binder and stabilizes it. Fig. 6 is a cellulose fiber structural unit. Table 4 lists some of the cellulose fiber properties [78].

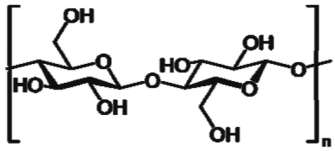

Fig. 6. Structural unit of cellulose fiber [78]

Table 4. Properties of Cellulose Fibers [78]

Property	Unit	Value
Specific Gravity	–	1.5
Bulk Density	g/cc	1600
Average fiber length	µm	20–2500
Average fiber diameter	1 m	25
pH value	–	3–11
Temperature resistance	°C	Up to 200
Solubility	–	Insoluble to water and organic solvent
Resistivity	–	Resistant to dilute acids and alkalis
Humidity	–	– Low natural humidity between 10 to 15% – Humidity upon delivery up to 4–9%

Cellulose fiber does not chemically modify bitumen but improves the finished product's physical properties by allowing higher bitumen contents. As a result, the bitumen does not run off the aggregate before compaction. Because cellulose fiber is fine and bulky, it necessitates distinct equipment and procedures to be mixed. Cellulose fiber can be provided in two basic forms: loose in small plastic bags for batch mixing [80], or mixed in by specially modified plants [27]. If mixed with asphalt, it forms a pelletized form that is easy to handle and add during mixing [27].

Natural cellulose fibers are physiologically and toxicologically safe. To stabilize the mix, only 0.3% cellulose fiber is needed. A lot of SMA is done with these fibers. Paper [22] investigated the fatigue performance of SMA mixes using COPF. They pulped COPF from empty fruit bunches in several ways. They found that SMA mixtures with cellulose oil palm fibers had better stability and resilient modulus.

Stone mastic asphalt and dense asphalt mixtures were compared in a study by [81] to define the influence of fiber reinforcement on fatigue and rutting. The fibers (cellulose and Polyacrylonitrile PAN) used in the test results have an impact on the material's properties. However, the difference in fiber use due to master curves is negligible. Fatigue behavior is strongly influenced by fibers, however. Up to six centimeters can be saved on the road base layer by using fibers. In some cases, plastic deformation can be reduced by up to 42%.

4.6. Coconut or coir fibers

The husk of a coconut can be used to make fiber. Thicker than any other natural fiber is coconut fiber. Coconut trees require warm, wet weather to thrive [2, 81, 82]. Coconut fiber is superior to other natural fibers due to its high lignin content and low cellulose and hemicellulose content, which gives it superior resilience, strength, damping, wear resistance, weather resistance, and elongation at break. Ropes, mats, mattresses, brushes, and many other products in the agricultural and building industries are all made from coir fiber [14, 33, 83, 84]. As can be seen in Fig. 7, coconut fiber has a distinct appearance [6].

Fig. 7. The appearance of coconut fiber [6]

Research [6] investigated the engineering properties of stone mastic asphalt containing coconut fiber. Various SMA mixtures were tested for their drain-down characteristics, static and repeated indirect tensile strength parameters, moisture susceptibility characteristics (tensile strength ratio), and retained stability. The Marshall properties of SMA mixes can be improved by only 0.3% coconut fiber. When fiber is included, SMA mixes benefit from improved drain-down, indirect tensile strength, and fatigue properties.

The use of coconut fibers in SMA mixtures was studied by [10] SMA mixtures were tested for drain-down, indirect tensile strength, resilient modulus, fatigue life, and moisture susceptibility. According to the results, the addition of coconut fiber did not appear to improve the cracking resistance of SMA mixtures; in fact, it reduced the number of cycles to failure compared to cellulose-based SMA mixtures.

Papers [85–87] have investigated the properties of SMA mixes with coir fibers and compared them with other types of natural fibers. The coir fibers were added to asphalt concrete mixtures at different percentages by weight. The results revealed that the addition of 0.3% fiber content was optimal for binder drain-down. The% drain-down proved coir fiber superiority over other types of fibers.

Research by [8] investigated the performance of coir fiber as a stabilizing agent for SMA mixtures. The engineering properties under static and repeated load conditions, as well as moisture susceptibility, were studied. The coconut fibers were cleaned and cut into

20–35 mm pieces to ensure proper mixing with the aggregates and binder. The addition of coir fiber up to 0.3% enhances the engineering attributes of SMA mixtures.

Coir's impact on SMA mixture compressive strength was studied by [42] Compressive strength tests are carried out after a preliminary investigation is completed in order to determine the resistance to crushing caused by traffic loads at a fiber content of 0.3%, all stabilized mixtures reach their maximum compressive strength. The higher compressive strength of coir fibers indicates a greater resistance to crushing.

4.7. Bagasse

Bagasse is a fibrillar component of many naturally occurring composites (wood, sugarcane straw, and bagasse) composed primarily of cellulose, glucose–polymer with a high modulus. After crushing and extracting sugarcane juice, a fibrous residue of cane stalks is left behind, increasing waste material [88]. To solve this issue, recycled sugarcane bagasse is used to decrease agricultural waste and yield low-cost SMA pavement that is both durable and reduces drainage issues. See Fig. 8 [89].

Fig. 8. Sugarcane Bagasse Fiber [89]

Paper [90] investigated the use of small cane fiber in improving the consistency and flow of Stone Mastic Asphalt Mixtures. Small cane fiber is a natural fiber that is less cost-effective than other non-traditional fibers. It has high tensile, flexural, and impact strength. The results of SMA mixes with different stabilizers were compared. Stabilizers were used up to 0.3% of the sample weight. Cane fiber can help improve SMA mixture stability.

5. Methods of sample preparation

The introduction of fibers can be accomplished in one of two ways: wet or dry. The fibers are incorporated into the asphalt cement before the binder is added. Before adding asphalt, the fiber is mixed with the aggregate in a dry process. The dry one is generally preferred over the wet one for a variety of reasons. The dry process is simpler, provides an even distribution of fiber in the final product, and reduces fiber balling or clumping in the mixture. In the meantime, the wet process does not appear to offer any unique advantages due to the fibers used not melting in the asphalt [14, 45, 90].

6. Effect of natural fibers

6.1. Effect of natural fibers on mixture properties

Researchers have turned their attention to the effects of hybridizing natural and synthetic fibers to enhance the fibers' mechanical properties. As synthetic fibers have a high initial cost, adverse environmental effects, and large energy demand, researchers began exploring natural fiber-based hybrid composites as an alternative. Natural fiber-based hybrid composites in asphalt reinforcement have received little to no attention in the literature. Table 5 shows effect of natural fiber on the mixture properties.

Table 5. Influence of natural fibers on the mixture attributes

Properties	Type of fiber	% of added fiber	Ref.	Main results
Marshall Stability	coir, sisal and banana	0.1%, 0.2%, 0.3%, and 0.4% by the weight of the mixture.	[92]	The optimum fiber content of the mix was 0.3% by the weight of mix for all the fiber mixes Among all the fibers used, coir fiber shows the best results, whereas sisal and banana fibers show same properties on stabilization.
	sisal	(0%-0.8%) of total aggregates	[93]	According to the results, Bituminous Concrete (BC) has a fiber content of (0.4%). When sisal fiber is added to a bituminous mixture, the mixture's stability, durability, air void, and flow value are all improved.
	coir		[94]	Enhanced fatigue life of bituminous mixes
	coir		[95]	According to these findings, the addition of coir stabilized and reduced the number of voids as the flow rate decreased. With a fiber content of 0.52% and a binder content of 5.72%, 15 mm long fibers with good volumetric and structural stability were produced.
	coir		[96]	Lower binder content has resulted from fiber reinforcement in bituminous mixes. The addition of coir fiber increased the Marshall Stability value significantly by 13%.

Continued on next page

Table 5 – *Continued from previous page*

Properties	Type of fiber	% of added fiber	Ref.	Main results
VMA	flocculent lignin fiber, mineral fiber, polyester fiber, blended fiber		[97]	No statistically significant difference was found between the stability of lignin fiber and polyester fiber in the mixture evaluation. In order to improve the performance of the mixture, mineral fibers necessitated a much higher fiber content than other fibers.
Air voids			[98] [29] [22]	Some fibers are better at absorbing oil than others, and fiber content impact VV.
	sisal fiber	0.4% and fiber length 10 mm	[93]	1. It was observed that after adding Sisal fiber by 0.4% and fiber length 10 mm, the stability of the mix increases, but when adding more than 0.4% fiber content, stability start to decrease. 2. It was identified that with increase in fiber content and fiber length up to a certain level, Air void and flow value decreases, thus the consistency of asphalt changes and becomes harder.
			[38] [16]	Due to a lack of binding material, the aggregates are separated by voids, which results in rising air voids.
Bulk Specific Gravity	flocculent lignin fiber, mineral fiber, polyester fiber, blended fiber		[97]	According to previous studies, SMA mixtures with a higher fiber content may not necessarily have a higher bulk specific gravity. Bulk-specific gravity is reduced as a result of the increased fiber content. Higher fiber content in SMA mixtures also improves asphalt absorption and adsorption.
Optimum fiber content			[97]	The minimum content is above 0.3% for mineral fiber and above 0.2% for the other fibers.
	coir fiber	10 mm length fiber	[99]	The addition of 0.3% fiber is found to be the optimum fiber content in SMA.
	cellulose and pelletized fiber		[27]	ITSM stiffness was increased by the addition of loose cellulose fiber up to an optimum level, above which stiffness decreased rapidly. Adding cellulose fibers such as this to SMA necessitates careful monitoring. An increase in the stiffness of the mix was observed when pelletized fiber was added.

6.2. Effect of natural fibers on mixture performance

SMA mixtures with different fibers as stabilizing additives are the subject of several research studies. The fibers make aggregate contact between stones and enhancing the bond between them easier. Reduced binder drain is one of the many benefits of including fibers in a formulation; With a variety of locally available fibers, the scope of the SMA study can be broadened. Table 6 shows the effect of Natural fiber on mixture performance.

Table 6. Effect of Natural fiber on mixture performance

Properties	Type of fiber	% of added fiber	Ref.	Main results
Rutting	cellulose fibers and mineral fibers (rock wool)	percentages (0.1–0.5%) of the total weight.	[100]	The highest ITS value and the least permanent deformation were observed in SMA samples made from 3% cellulose-GER (Made in Germany), according to laboratory tests, indicating that fiber type and content variation can lead to significant changes in rutting performance.
	bamboo fiber	were 0.2–0.3% for dense-graded mixtures and 0.4% for SMA mixtures.	[55]	The asphalt mixtures that included bamboo fiber had better resistance to rutting and low-temperature cracking.
	jute fibers, waste fibers, and Natural fibers		[9]	Stabilizers made from jute fibers improved rut resistance in natural fibers. Stabilizing SMA with FERP in waste fibers improved rut resistance, as did SMA mixed with FERP. Waste and synthetic fibers are less resistant to permanent deformation when compared to natural and man-made fibers.
	cellulose and mineral fibers		[101]	Small amounts (0.3%) reduce binder drainage, but larger additions may have unexpected effects on in-service properties like cohesiveness, stiffness, and resistance to permanent deformation. These properties must be taken into account if in-service performance prediction is the goal of the project.
Moisture induced damage	cellulose fibers		[29]	Researchers compared SMA mixtures made with waste fibers and cellulose and found that both moisture-induced damage and rutting were the same.

Continued on next page

Table 6 – *Continued from previous page*

Properties	Type of fiber	% of added fiber	Ref.	Main results
Moisture induced damage	bamboo fiber	were 0.2–0.3% for dense-graded mixtures and 0.4% for SMA mixtures.	[55]	Immersion Marshall and freeze-thaw cycling tests showed that all mixtures were moisture resistant to a satisfactory level in all cases.
	banana fiber (BF) and pelletized fiber (VP)		[15]	Polymer-modified SMA mixtures were found to have similar resistance to rutting, moisture-induced damage, and fatigue compared to SMA mixtures with natural and pelletized fibers.
Drain-down	coir fiber and pineapple fiber	Five different bitumen concentrations, ranging from 5.5% to 7%, are chosen for this analysis.	[85]	The test results have revealed that the use of fibers reduced the drain-down value and maximum stability value for coir fiber when compared with pineapple fiber
	sugarcane bagasse fiber	0.3% by total weight of SMA mixtures and fiber length of 6mm is added	[89]	A greater rut depth (1.945 mm) was measured for SMA Mix that did not contain sugarcane bagasse fiber (1.635 mm) Natural fiber has both ecological and economic benefits.
	banana fiber (BF) and pelletized fiber (VP)		[15]	Including natural and pelletized fiber in the SMA mixture reduced binder drain-down and increased durability against rutting, fatigue, and moisture damage.
		4% to 7% of binder contents and fiber content varied 0 to 0.5% maximum of the total mix	[102]	
	coir fiber	10 mm length fiber	[99]	As a result of drain down tests, coir fiber retards the drain down of the binder, and the 10 mm length and 0.3% fiber provides good results compared to the traditional mix.
	jute fibers and waste fibers		[9]	The rate at which asphalt drains is significantly affected by the stabilizer type. Compared to SMA mixes stabilized with other fibers, those stabilized with FERP exhibited less drain-down.

Continued on next page

Table 6 – *Continued from previous page*

Properties	Type of fiber	% of added fiber	Ref.	Main results
Drain-down	cellulose and mineral fibers		[101]	Traditional SMA mixture drain down was higher than allowed, but all the additives used were effective in reducing it to meet the specified requirement. Using mineral and cellulose fibers as drain-down inhibitors proved to be more effective than SBS.
	coir, sisal, banana fibers (natural fibers)		[42]	Fiber stabilizers have been found to be more effective than polymer materials in decreasing the drain-down of the SMA mixture because of their absorptive properties. The coir fiber additive is the most effective of the fibers tested. Both Sisal and Banana Fiber Mixtures had similar Stabilization Properties.

7. Conclusions

This paper's subject was the use of natural fibers and their composites to alter asphalt concrete, particularly SMA mixtures. The use of natural fibers such as coir, sisal, hemp, jute, and palm in modifying asphalt concrete is reviewed. The following conclusions can be drawn from the literature:

1. Bituminous mixture mechanical properties can be improved through the utilization of natural fibers.
2. Natural fibers can be used as a substitution for synthetic fibers in SMA mixtures because of their excellent adhesion to asphalt.
3. Natural fibers appear to increase the asphalt binder's stiffness, resulting in stiffer mixes with less binder drain-down and longer fatigue life.
4. Incorporating fibers into the mix helps to keep binders from drain-down.
5. Fiber-rich mixtures showed reduced void content and greater resistance to permanent deformation compared to those without fibers.

8. Research works for the future

A key area of research in the utilization of fiber composites in asphalt concrete should focus on fiber content, and length changes. Additionally, more effort must be done to improve the fibers' length, width, form, and orientation. Fiber-modified asphalt concrete must also be tested in the field to determine the influence of the surrounding environment on test findings. The use of composite science techniques to model the mechanical properties of fiber-reinforced asphalt concrete mixtures might be considered a new research area.

New jute-based products and technologies are constantly being developed through research and development in both the producing and consuming countries. People around the world are becoming more aware of the importance of maintaining a pollution-free environment, and as a result, they are more likely to opt for natural fiber products, which are both environmentally friendly and functional. Therefore, natural fiber industries necessitate concerted efforts to ensure long-term viability. To increase demand on the global market, it is necessary to raise the profile of natural fibers.

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References

[1] N.S.S.M. Zali, et al., "Properties of stone mastic asphalt incorporating nano titanium as binder's modifier", Archives of Civil Engineering, vol. 68, no. 1, pp. 653–666, 2022, doi: 10.24425/ace.2022.140192.

[2] S. Awanti, "Laboratory evaluation of SMA mixes prepared with SBS modified and neat bitumen", *Procedia-Social and Behavioral Sciences*, vol. 104, pp. 59–68, 2013, doi: 10.1016/j.sbspro.2013.11.098.

[3] V. Yadykina, S. Tobolenko, A. Trautvain, and A. Zhukova, "The influence of stabilizing additives on physical and mechanical properties of stone mastic asphalt concrete", *Procedia Engineering*, vol. 117, pp. 376–381, 2015, doi: 10.1016/j.proeng.2015.08.181.

[4] B.M. Harris and K.D. Stuart, "Analysis of mineral fillers and mastics used in stone matrix asphalt", *Asphalt Paving Technology*, vol. 64, pp. 54–95, 1995.

[5] J. Serfass and J. Samanos, "Fiber-modified asphalt concrete characteristics, applications and behavior", *Asphalt Paving Technology*, vol. 65, pp. 193–230, 1996.

[6] A. Suchismita, "A study of effects of binder quality and natural fiber on stone matrix asphalt mixtures", MSc. thesis, 2009.

[7] F.M. Nejad, E. Aflaki, and M. Mohammadi, "Fatigue behavior of SMA and HMA mixtures", *Constrution and Building Materials*, vol. 24, no. 7, pp. 1158–1165, 2010, doi: 10.1016/j.conbuildmat.2009.12.025.

[8] M. Panda, A. Suchismita, and J. Giri, "Utilization of ripe coconut fiber in stone matrix asphalt mixes", *International Journal of Transportation Science and Technology*, vol. 2, no. 4, pp. 289–302, 2013, doi: 10.1260/2046-0430.2.4.289.

[9] K. Raghuram and V. Chowdary, "Performance evaluation of stone matrix asphalt (SMA) using low cost fibres", *Journal of the Indian Roads Congress*, vol. 74, no. 2, pp. 1–159, 2013.

[10] A.C. d. Vale, M.D.T. Casagrande, and J.B. Soares, "Behavior of natural fiber in stone matrix asphalt mixtures using two design methods", *Journal of Materials in Civil Engineering*, vol. 26, no. 3, pp. 457–465, 2014, doi: 10.1061/(ASCE)MT.1943-5533.0000815.

[11] R.M. Xavier, B. Martin, L.A. Babu, L.E. Jose, and L. Roy, "A review on fiber modified stone matrix asphalt", *International Research Journal of Engineering and Technology*, vol. 5, no. 3, pp. 3018–3020, 2018.

[12] K. Kavalakuntla and B. Praveen, "An experimental study of bituminous mixes using a natural fibre", *International Journal and Magazine of Engineering Technology, Management and Research*, vol. 3, no. 11, pp. 906–912, 2016.

[13] V. Sharma and S. Goyal, "Comparative study of performance of natural fibres and crumb rubber modified stone matrix asphalt mixtures", *Canadian Journal of Civil Engineering*, vol. 33, no. 2, pp. 134–139, 2006, doi: 10.1139/l05-096.

[14] O. Abiola, W. Kupolati, E. Sadiku, and J. Ndambuki, "Utilisation of natural fibre as modifier in bituminous mixes: A review", *Construction and Building Materials*, vol. 54, pp. 305–312, 2014, doi: 10.1016/j.conbuildmat.2013.12.037.

[15] G. Shiva Kumar, A.R. Shankar, and B. Ravi Teja, "Laboratory evaluation of SMA mixtures made with polymer-modified bitumen and stabilizing additives", *Journal of Materials in Civil Engineering*, vol. 31, no. 4, 2019, doi: 10.1061/(ASCE)MT.1943-5533.0002652.

[16] H. Chen, Q. Xu, S. Chen, and Z. Zhang, "Evaluation and design of fiber-reinforced asphalt mixtures", *Materials & Design*, vol. 30, no. 7, pp. 2595–2603, 2009, doi: 10.1016/j.matdes.2008.09.030.

[17] I.M. Asi, "Laboratory comparison study for the use of stone matrix asphalt in hot weather climates", *Construction and Building Materials*, vol. 20, no. 10, pp. 982–989, 2006, doi: 10.1016/j.conbuildmat.2005.06.011.

[18] P. Kumar, P. Sikdar, S. Bose, and S. Chandra, "Use of jute fibre in stone matrix asphalt", *Road Materials and Pavement Design*, vol. 5, no. 2, pp. 239–249, 2004, doi: 10.1080/14680629.2004.9689971.

[19] D.V. Thanh and P. Cheng, "Influence of different fibers on high temperature and water stability of stone matrix asphalt", *International Journal of Applied Engineering and Technology*, vol. 3, no. 1, pp. 1–10, 2013.

[20] A.M. Moghaddam, S.A. Ziaee, H.F. Mollashahi, and M. Jalili Qazizadeh, "Effects of waste fibers stabilizers on the draindown and moisture damage sensitivity properties of SMA mixtures", *International Journal of Transportation Engineering*, vol. 2, no. 2, pp. 155-165, 2014, doi: 10.22119/ijte.2014.7877.

[21] E. Brown, R.B. Mallick, J.E. Haddock, and J. Bukowski, *Performance of stone matrix asphalt (SMA) mixtures in the United States*. National Center for Asphalt Technology, 1997.

[22] R. Muniandy and B.B.K. Huat, "Laboratory diameteral fatigue performance of stone matrix asphalt with cellulose oil palm fiber", *American Journal of Applied Sciences*, vol. 3, no. 9, pp. 2005–2010, 2006, doi: 10.3844/ajassp.2006.2005.2010.

[23] G. Shiva Kumar, A.U.R. Shankar, and B.V.S. Ravi Teja, "Laboratory evaluation of SMA mixtures made with polymer-modified bitumen and stabilizing additives", *Journal of Materials in Civil Engineering*, vol. 31, no. 4, 2019, doi: 10.1061/(asce)mt.1943-5533.0002652.

[24] S.J. Lee, J.P. Rust, H. Hamouda, Y.R. Kim, and R.H. Borden, "Fatigue cracking resistance of fiber-reinforced asphalt concrete", *Textile Research Journal*, vol. 75, no. 2, pp. 123–128, 2005, doi: 10.1177/004051750507500206.

[25] P.S. Kandhal, K.Y. Foo, and R.B. Mallick, "Critical review of voids in mineral aggregate requirements in Superpave", *Transportation Research Record*, vol. 1609, no. 1, pp. 21–27, 1998.

[26] J. Richardson, *Stone mastic asphalt in the Uk symposium on stone mastic asphalt and thin surfacing*. London: Richter E, 1997.

[27] A. Woodside, W. Woodward, and H. Akbulut, "Stone mastic asphalt: assessing the effect of cellulose fibre additives", in *Proceedings of the institution of civil engineers-municipal engineer*, vol. 127, no. 3. Thomas Telford-ICE Virtual Library, 1998, pp. 103–108.

[28] Y. Xue, H. Hou, S. Zhu, and J. Zha, "Utilization of municipal solid waste incineration ash in stone mastic asphalt mixture: Pavement performance and environmental impact", *Construction and Building Materials*, vol. 23, no. 2, pp. 989–996, 2009, doi: 10.1016/j.conbuildmat.2008.05.009.

[29] B.J. Putman and S.N. Amirkhanian, "Utilization of waste fibers in stone matrix asphalt mixtures", *Resources, Conservation and Recycling*, vol. 42, no. 3, pp. 265–274, 2004, doi: 10.1016/j.resconrec.2004.04.005.

[30] C. Kamaraj, P. Jain, B. Sharma, and S. Gangopadhyay, "Design, construction and performance of stone matrix asphalt (SMA)–field test section", *Highway Research Journal*, vol. 6, no. 13, pp. 12–25, 2013.

[31] P. Peltonen, "Wear and deformation characteristics of fibre reinforced asphalt pavements", *Construction and Building Materials*, vol. 5, no. 1, pp. 18–22, 1991.

[32] H.F. Hassan, S. Al-Oraimi, and R. Taha, "Evaluation of open-graded friction course mixtures containing cellulose fibers and styrene butadiene rubber polymer", *Journal of Materials in Civil Engineering*, vol. 17, no. 4, pp. 416–422, 2005, doi: 10.1061/(ASCE)0899-1561(2005)17:4(416).

[33] M. Razahi and A. Chopra, "A review of using ssisal fiber and coir fiber as additives in stone matrix asphalt", *International Research Journal of Engineering and Technology*, vol. 7, no. 2, pp. 1692–1697, 2020.

[34] H. Huang and T.D. White, "Dynamic properties of fiber-modified overlay mixture", *Transportation Research Record*, vol. 1545, no. 1, pp. 98–104, 1996.

[35] S. Wu, Q. Ye, N. Li, and H. Yue, "Effects of fibers on the dynamic properties of asphalt mixtures", *Journal of Wuhan University of Technology-Materials Science Ed.*, vol. 22, no. 4, pp. 733–736, 2007, doi: 10.1007/s11595-006-4733-3.

[36] D.A. Maurer and G.J. Malasheskie, "Field performance of fabrics and fibers to retard reflective cracking", *Geotextiles and Geomembranes*, vol. 8, no. 3, pp. 239–267, 1989.

[37] S. Tapkın, "The effect of polypropylene fibers on asphalt performance", *Building and Environment*, vol. 43, no. 6, pp. 1065–1071, 2008, doi: 10.1016/j.buildenv.2007.02.011.

[38] M.A. Cleven, "Investigation of the properties of carbon fiber modified asphalt mixtures", M.A. thesis, Michigan Technological University, Houghton, 2000.

[39] A. Kulkarni, K. Satyanarayana, K. Sukumaran, and P. Rohatgi, "Mechanical behaviour of coir fibres under tensile load", *Journal of Materials Science*, vol. 16, no. 4, pp. 905–914, 1981.

[40] S. Tapkın, A. Çevik, and Ü. Uşar, "Prediction of Marshall test results for polypropylene modified dense bituminous mixtures using neural networks", *Expert Systems with Applications*, vol. 37, no. 6, pp. 4660–4670, 2010, doi: 10.1016/j.eswa.2009.12.042.

[41] L.A. Cooley and E.R. Brown, *Potential of using stone matrix asphalt (SMA) for thin overlays*. NCAT, 2003.

[42] C. Bindu and K. Beena, *Influence of additives on the drain down characteristics of stone matrix asphalt mixtures*. 2014.

[43] G. K. Allen, "Problems of stone mastic asphalt use in North Queensland", Bachelor of Engineering Civil, Faculty of Engineering and Surveying, University of Southern Queensland, 2006.

[44] P. Kumar, S. Chandra, and S. Bose, "Laboratory investigations on SMA mixes with different additives", *International Journal of Pavement Engineering*, vol. 8, no. 1, pp. 11–18, 2007, doi: 10.1080/10298430600987381.

[45] S.M. Abtahi, M. Sheikhzadeh, and S.M. Hejazi, "Fiber-reinforced asphalt-concrete–a review", *Construction and Building Materials*, vol. 24, no. 6, pp. 871–877, 2010, doi: 10.1016/j.conbuildmat.2009.11.009.

[46] A. Al-Hadidy and Y.-q. Tan, "Performance of the SMA mixes made with the various binders", *Construction and Building Materials*, vol. 25, no. 9, pp. 3668–3673, 2011, doi: 10.1016/j.conbuildmat.2011.03.008.

[47] C. Bindu and K. Beena, "Waste plastic as a stabilizing additive in Stone Mastic Asphalt", *International Journal of Engineering and Technology*, vol. 2, no. 6, pp. 379-387, 2010.

[48] Y.G. Thyavihalli Girijappa, S. Mavinkere Rangappa, J. Parameswaranpillai, and S. Siengchin, "Natural fibers as sustainable and renewable resource for development of eco-friendly composites: a comprehensive review", *Frontiers in Materials*, vol. 6, 2019, doi: 10.3389/fmats.2019.00226.

[49] P. Manimaran, P. Senthamaraikannan, M. Sanjay, M. Marichelvam, and M. Jawaid, "Study on characterization of Furcraea foetida new natural fiber as composite reinforcement for lightweight applications", *Carbohydrate Polymers*, vol. 181, pp. 650–658, 2018, doi: 10.1016/j.carbpol.2017.11.099.

[50] R. Mahjoub, J.M. Yatim, A.R.M. Sam, and S.H. Hashemi, "Tensile properties of kenaf fiber due to various conditions of chemical fiber surface modifications", *Construction and Building Materials*, vol. 55, pp. 103–113, 2014, doi: 10.1016/j.conbuildmat.2014.01.036.

[51] D. Athith, et al., "Effect of tungsten carbide on mechanical and tribological properties of jute/sisal/E-glass fabrics reinforced natural rubber/epoxy composites", *Journal of Industrial Textiles*, vol. 48, no. 4, pp. 713–737, 2017, doi: 10.1177/1528083717740765.

[52] W. Liu, A.K. Mohanty, L.T. Drzal, and M. Misra, "Novel biocomposites from native grass and soy based bioplastic: processing and properties evaluation", *Industrial and Engineering Chemistry Research*, vol. 44, no. 18, pp. 7105–7112, 2005, doi: 10.1021/ie050257b.

[53] O. Faruk, A.K. Bledzki, H.P. Fink, and M. Sain, "Progress report on natural fiber reinforced composites", *Macromolecular Materials and Engineering*, vol. 299, no. 1, pp. 9–26, 2014, doi: 10.1002/mame.201300008.

[54] S. Oda, J.L. Fernandes, and J.S. Ildefonso, "Analysis of use of natural fibers and asphalt rubber binder in discontinuous asphalt mixtures", *Construction and Building Materials*, vol. 26, no. 1, pp. 13–20, 2012, doi: 10.1016/j.conbuildmat.2011.06.030.

[55] Y. Sheng, B. Zhang, Y. Yan, H. Li, Z. Chen, and H. Chen, "Laboratory investigation on the use of bamboo fiber in asphalt mixtures for enhanced performance", *Arabian Journal for Science and Engineering*, vol. 44, no. 5, pp. 4629-4638, 2019, doi: 10.1007/s13369-018-3490-x.

[56] P. Zakikhani, R. Zahari, M. Sultan, and D. Majid, "Extraction and preparation of bamboo fibre-reinforced composites", *Materials and Design*, vol. 63, pp. 820–828, 2014, doi: 10.1016/j.matdes.2014.06.058.

[57] G. Wang and F. Chen, "Development of bamboo fiber-based composites", in *Advanced high strength natural fibre composites in construction*. Elsevier, 2017, pp. 235–255, doi: 10.1016/B978-0-08-100411-1.00010-8.

[58] M. Fan and B. Weclawski, "Long natural fibre composites", in *Advanced high strength natural fibre composites in construction*. Elsevier, 2017, pp. 141–177, doi: 10.1016/B978-0-08-100411-1.00006-6.

[59] J.E. van Dam, H.W. Elbersen, and C.M.D. Montańo, "Bamboo production for industrial utilization", in *Perennial grasses for bioenergy and bioproducts*. Elsevier, 2018, pp. 175–216, doi: 10.1016/B978-0-12-812900-5.00006-0.

[60] J. J. Janssen, *Designing and building with bamboo*. International Network for Bamboo and Rattan Netherlands, 2000.

[61] Y. Rajesh, P. Nadiu, and P. Kumar, "Experimental study–the use of bamboo fiber using SMA methodology in coarse aggregates", *International Journal for Modern Trends in Science and Technology*, vol. 3, no. 10, pp. 72–88, 2017.

[62] H. Jia et al., "Effects of bamboo fiber on the mechanical properties of asphalt mixtures", *Construction and Building Materials*, vol. 289, art. no. 123196, 2021, doi: 10.1016/j.conbuildmat.2021.123196.

[63] M.D. Alotaibi et al., "Characterization of natural fiber obtained from different parts of date palm tree (Phoenix dactylifera L.)", *International Journal of Biological Macromolecules*, vol. 135, pp. 69–76, 2019, doi: 10.1016/j.ijbiomac.2019.05.102.

[64] D. Rivera, C. Obón, F. Alcaraz, E. Laguna, and D. Johnson, "Date-palm (Phoenix, Arecaceae) iconography in coins from the Mediterranean and West Asia (485 BC–1189 AD)", *Journal of Cultural Heritage*, vol. 37, pp. 199–214, 2019, doi: 10.1016/j.culher.2018.10.010.

[65] M.H. Gheith et al., "Flexural, thermal and dynamic mechanical properties of date palm fibres reinforced epoxy composites", *Journal of Materials Research and Technology*, vol. 8, no. 1, pp. 853–860, 2019, doi: 10.1016/j.jmrt.2018.06.013.

[66] T. Masri, H. Ounis, L. Sedira, A. Kaci, and A. Benchabane, "Characterization of new composite material based on date palm leaflets and expanded polystyrene wastes", *Construction and Building Materials*, vol. 164, pp. 410–418, 2018, doi: 10.1016/j.conbuildmat.2017.12.197.

[67] K. Senthilkumar et al., "Mechanical properties evaluation of sisal fibre reinforced polymer composites: A review", *Construction and Building Materials*, vol. 174, pp. 713–729, 2018, doi: 10.1016/j.conbuildmat.2018.04.143.

[68] A. Devaraju and R. Harikumar, "Life cycle assessment of sisal fiber", in *Encyclopedia of Renewable and Sustainable Materials,* vol. 2. Elsevier, 2020, pp. 144–155, doi: 10.1016/B978-0-12-803581-8.10552-1.

[69] N. Chand, R. Tiwary, and P. Rohatgi, "Bibliography resource structure properties of natural cellulosic fibres – an annotated bibliography", *Journal of Materials Science*, vol. 23, no. 2, pp. 381–387, 1988.

[70] M. Aslan, M. Tufan, and T. Küçükömeroğlu, "Tribological and mechanical performance of sisal-filled waste carbon and glass fibre hybrid composites", *Composites Part B: Engineering*, vol. 140, pp. 241–249, 2018, doi: 10.1016/j.compositesb.2017.12.039.

[71] U. Nirmal, J. Hashim, and M.M. Ahmad, "A review on tribological performance of natural fibre polymeric composites", *Tribology International*, vol. 83, pp. 77–104, 2015, doi: 10.1016/j.triboint.2014.11.003.

[72] S. Oda, J. L. Fernandes Jr., and J. S. Ildefonso, "Analysis of use of natural fibers and asphalt rubber binder in discontinuous asphalt mixtures", *Construction and Building Materials*, vol. 26, no. 1, pp. 13–20, 2012, doi: 10.1016/j.conbuildmat.2011.06.030.

[73] D. Kar, J.P. Giri, and M. Panda, "Performance evaluation of bituminous paving mixes containing sisal fiber as an additive", *Transportation Infrastructure Geotechnology*, vol. 6, no. 3, pp. 189–206, 2019, doi: 10.1007/s40515-019-00079-6.

[74] S. Das, "Mechanical properties of waste paper/jute fabric reinforced polyester resin matrix hybrid composites", *Carbohydrate Polymers*, vol. 172, pp. 60–67, 2017, doi: 10.1016/j.carbpol.2017.05.036.

[75] S. Shahinur and M. Hasan, "Natural fiber and synthetic fiber composites: comparison of properties, performance, cost and environmental benefits", in *Encyclopedia of Renewable and Sustainable Materials,* vol. 2. Elsevier, 2020, pp. 794–802, doi: 10.1016/B978-0-12-803581-8.10994-4.

[76] M.S. Rahman, "Jute–a versatile natural fibre. Cultivation, extraction and processing", in *Industrial applications of natural fibres: structure, properties and technical applications*, vol. 1. Wiley, 2010.

[77] P.K. Banerjee and M. Ghosh, "Studies on jute–asphalt composites", *Journal of Applied Polymer Science*, vol. 109, no. 5, pp. 3165–3172, 2008, doi: 10.1002/app.28325.

[78] S. Bose, C. Kamraj, and P. Nanda, "Stone matrix asphalt (SMA) – a long life pavement surface", presented at *International Seminar on Innovations in Construction and Maintenance of Flexible Pavements*, Agra. 2-4 September 2006.

[79] B. Schneider, *Stone mastic asphalt*. Regional Export Manager, Road Construction Division, J. Rettenmaier & Sohne, Germany, 2000.

[80] C. Weise and A. Zeissler, "Effects of fiber reinforcement on the fatigue and rutting performance of asphalt mixes", presented at the Proceedings of 6th Eurasphalt & Eurobitume Congress, 2016, doi: 10.14311/EE.2016.015.

[81] H. Danso, "Properties of coconut, oil palm and bagasse fibres: as potential building materials", *Procedia Engineering*, vol. 200, pp. 1–9, 2017, doi: 10.1016/j.proeng.2017.07.002.

[82] X. Arulandoo, K. Sritharan, and M. Subramaniam, "The coconut palm", in *Encyclopedia of Applied Plant Sciences*, vol. 3. Elsevier, 2017, pp. 426–430, doi: 10.1016/B978-0-12-394807-6.00237-9.

[83] J.C. dos Santos, R. L. Siqueira, L.M.G. Vieira, R.T.S. Freire, V. Mano, and T.H. Panzera, "Effects of sodium carbonate on the performance of epoxy and polyester coir-reinforced composites", *Polymer Testing*, vol. 67, pp. 533–544, 2018, doi: 10.1016/j.polymertesting.2018.03.043.

[84] S. Sengupta and G. Basu, "Chapter 04122 - Properties of coconut fiber", in *Reference Module in Materials Science and Materials Engineering*. 2017, pp. 1–20, doi: 10.1016/B978-0-12-803581-8.04122-9.

[85] M. Satyavathi, B.S. Rao, and G.V. Rao, "Experimental study of stone matrix asphalt with coir fiber and pineapple fiber", *International Journal of Engineering Sciences & Research Technology*, vol. 5, no. 11, pp. 378–385, 2016, doi: 10.5281/zenodo.167081.

[86] K. Shravan and K.B.R.P. Reddy, "A comparative study on performance of stone matrix asphalt with cellulose and coir fiber", *International Journal of Advance Research and Innovative Ideas in Education*, vol. 3, no. 6, pp. 795–804, 2017.

[87] P. C. Shekar, B. Rajath, and J. Vishwas, "Experimental investigation of stone mastic asphalt by varying mix design", *International Research Journal of Engineering and Technology (IRJET)*, vol. 5, no. 5, 2018.

[88] S.M. d. Luz, A.R. Goncalves, and A. Del'Arco Jr., "Mechanical behavior and microstructural analysis of sugarcane bagasse fibers reinforced polypropylene composites", *Composites Part A: Applied Science and Manufacturing*, vol. 38, no. 6, pp. 1455–1461, 2007, doi: 10.1016/j.compositesa.2007.01.014.

[89] S. Mansor, N.I. Zainuddin, N.A. Aziz, M. Razali, and M.I. Joohari, "Sugarcane bagasse fiber – An eco-friendly pavement of SMA", in *AIP Conference Proceedings*, vol. 2020, no. 1, 2018, doi: 10.1063/1.5062658.

[90] P. Prakash and R. Palya, "Utilization of bamboo fiber in improving the properties of stone matrix asphalt mixes", *International Journal of Mechanical And Production Engineering*, vol. 5, no. 11, 2017.

[91] M. Labib and A. Maher, *Recycled plastic fibers for asphalt mixtures*. 1999.

[92] S. Dilkusha and K.V. Manikanta, "Laboratory investigations of stone matrix asphalt by using natural fibres", *International Journal for Science and Advance Research In Technology*, vol. 4, no. 8, p. 424, 2018.

[93] A. Kundal and A. Goel, "A study of bituminous mixes with natural fibre (sisal fibre) by experiment", *Journal of Chemical Information and Modeling*, vol. 53, pp. 1689–1699, 2019.

[94] N. Panda, "Laboratory investigations on stone matrix asphalt using sisal fibre for Indian roads", thesis, *National Institute of Technology, Rourkela,* 2010.

[95] K. Thulasirajan and V. Narasimha, "Studies on coir fibre reinforced bituminous concrete", *International Journal of Earth Sciences and Engineering*, vol. 4, no. 6, pp. 835-838, 2011.

[96] T. Subramani, "Experimental investigations on coir fibre reinforced bituminous mixes", *International Journal of Engineering Research and Applications*, vol. 2, no. 3, pp. 1794–1804, 2012.

[97] Y. Sheng, H. Li, P. Guo, G. Zhao, H. Chen, and R. Xiong, "Effect of fibers on mixture design of stone matrix asphalt", *Applied Sciences*, vol. 7, no. 3, 2017, doi: 10.3390/app7030297.

[98] Z. Fu, Y. Dang, B. Guo, and Y. Huang, "Laboratory investigation on the properties of asphalt mixtures modified with double-adding admixtures and sensitivity analysis", *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 3, no. 5, pp. 412–426, 2016, doi: 10.1016/j.jtte.2016.09.002.

[99] B.G. Raju and K.N.S. Rao, "Characterization of fibre reinforced bituminous mixes", *International Journal of Science and Research (IJSR)*, vol. 4, no. 12, pp. 802-806, 2015.

[100] H. Behbahani, S. Nowbakht, H. Fazaeli, and J. Rahmani, "Effects of fiber type and content on the rutting performance of stone matrix asphalt", *Journal of Applied Sciences*, vol. 9, no. 10, pp. 1980–1984, 2009, doi: 10.3923/jas.2009.1980.1984.

[101] A. Mokhtari and F. Moghadas Nejad, "Mechanistic approach for fiber and polymer modified SMA mixtures", *Construction and Building Materials*, vol. 36, pp. 381–390, 2012, doi: 10.1016/j.conbuildmat.2012.05.032.

[102] D. Kar, "A laboratory study of bituminous mixes using a natural fibre", MSc. thesis, National Institute of Technology, Rourkela, 2012.

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